

SEARCHING FOR BLACK HOLES

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Final Report

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Principal Investigator
Dr. M. Garcia

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Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

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Our UV/VIS work concentrates on black hole x-ray nova. These objects consist of two stars in close orbit, one of which we believe is a black hole — our goal is to SHOW that one is a black hole. In order to reach this goal we carry out observations in the Optical, UV, IR and x-ray bands, and compare the observations to theoretical models.

In the past year, our UV/VIS grant has provided partial support (mainly travel funds and page charges) for work we have done on x-ray nova containing black holes and neutron stars. We have been very successful in obtaining telescope time to support our project - we have completed approximately a dozen separate observing runs averaging 3 days each, using the MMT (5M), Lick 3M, KPNO 2.1M, CTIO 4M, CTIO 1.5M, and the SAO/WO 1.2M telescopes. These observations have allowed the identification of one new black hole (Nova Oph 1977), and allowed the mass of another to be measured (GS2000+25). Perhaps our most exciting new result (below) is the evidence we have gathered for the existence of 'event horizons' in black hole x-ray nova.

1 Advection-Dominated Accretion and Black Hole Event Horizons

One of our most promising new results came from a comparison of black hole x-ray nova and their cousins, neutron star x-ray nova. Because black holes have an event horizon, from which nothing (not even light) can escape, they could (if seen under the right conditions) act like cosmic 'vacuum cleaners'. By comparing the outburst and quiescent properties of black hole and neutron star x-ray nova, we have found evidence for this 'vacuum cleaner' like effect. This result is especially exciting because the event horizon is one of the defining characteristics of a black hole, and evidence for its existence has been very difficult to find. This result will be highlighted at the upcoming Jan 1997 AAS conference in Toronto, with an invited talk by Ramesh Narayan, a poster by Garcia, Narayan and McClintock, and a press conference. The abstract of our paper (submitted to ApJ Letters) is below.

"Advection-Dominated Accretion and Black Hole Event Horizons"
Ramesh Narayan, Michael R. Garcia, and Jeffrey E. McClintock
Submitted to ApJ Letters Nov 1, 1996

The defining characteristic of a black hole is that it possesses an event horizon through which matter and energy can fall in but from which nothing escapes. Soft X-ray transients (SXTs), a class of X-ray binaries, appear to confirm this fundamental property of black holes. SXTs that are thought to contain accreting black holes display a large variation of luminosity between their bright and faint states, while SXTs with accreting neutron stars have a smaller variation. This difference is predicted if the former stars have horizons and the latter have normal surfaces.

2 A Black Hole in X-ray Nova Oph 1977

Observations by Remillard, Orosz, McClintock, and Bailyn of an x-ray nova first discovered in 1977, and now in quiescence, show that the primary in this system is likely to be a black hole. The abstract of the paper published in the 1996 ApJ (459, 226) is below.

Dynamical Evidence for a Black Hole in X-Ray Nova Ophiuchi 1977

Remillard, R.A., Orosz, J. A., McClintock, J.E., Bailyn, C. D., ApJ 459, 226

We have conducted spectral and photometric observations of the quiescent optical counterpart of X-ray Nova Ophiuchi 1977 (H1705-250; V2107 Oph) at CTIO. Fifty hours of photometry during 1994 July reveal a typical double-wave modulation of $\pm 0.2\text{mag}$ with a period of 12.51 ± 0.03 hr. The mean brightness was $V = 21.5$. Forty spectra (2000 s exposures) were obtained in 1994 July and 13 similar spectra were obtained in 1993 May. We derived the absorption-line radial velocities using two conventional cross-correlation techniques. Both of them suggest a velocity semiamplitude (K) in excess of 400 km/sec, but only half or less of the spectra could be utilized because the signal-to-noise ratio is so low. Consequently, we devised a new and powerful "restframe search" technique that uses all of the available data. For each of several million binary ephemerides, we summed all of the spectra in a trial restframe of the secondary star, and each restframe spectrum was cross-correlated against a template spectrum with a well-known velocity. We then searched for the set of orbital parameters that produced the strongest cross-correlation value. The results confirmed the photometric period and the best restframe spectrum has a highly significant correlation ($r \sim 6$) against a broad range of K star templates. The best value for the velocity amplitude is $K = 420 \pm 30$ km/sec. The corresponding mass function is $f(M) = 4.0 \pm 0.8 M_{\text{sun}}$. The probability is high that the compact object exceeds the maximum mass ($3M_{\text{sun}}$) for a neutron star. Furthermore, this nova is very similar in many respects to the dynamical black hole binaries, A0620-00 and X-ray Nova Muscae 1991. We conclude that X-ray Nova Oph 1977 is the sixth confirmed example of an X-ray binary with a black hole primary. The estimated magnitude of the secondary star is $V \sim 22.0$. This distance to the binary system is 6 kpc, if the companion is a K3 star near the main sequence. Double-peaked H α emission suggests low levels of accretion 17 yr after outburst, similar to the behavior seen in A0620-00. Unusual structure in the H α line profile was observed during 1994 July, and its cause remains unexplained. The most straightforward interpretations of the light curves confine the binary inclination angle to the range of $60 < i < 80^\circ$. In that case, the mass of the black hole primary is $6 \pm 1 M_{\text{sun}}$, if the companion is a K3 star on the main sequence.

3 GS200+25 IR Lightcurve

Measuring the infrared lightcurve of quiescent black hole x-ray nova is the most secure way to determine the mass of the black hole. We have done this for GS2000+25 using the Lick

3M telescope. Our results are published in the 1996 ApJ (470, L57). The abstract is below.

On the Mass of the Black Hole in GS2000+25

P. Callanan, M. Garcia, A. Filippenko, I. McLean and H. Teplitz, 1996 ApJL 470, L57.

We present J- and K'-band ($1.95-2.35\mu$) photometry of the quiescent X-ray nova GS 2000+25, obtained in an attempt to constrain the mass of the compact object (M_X). Combined with the mass function of $4.97M_{sun}$, the infrared light curves imply $M_X \leq 11M_{sun}$ (90% confidence level), regardless of the evolutionary state of the secondary, for a mass ratio q of $4 < q < 30$. For a secondary mass in the range $M_2 = 0.4 - 0.9M_{sun}$ (as expected for a K dwarf companion), and assuming a negligible contribution from the disk at these wavelengths, we find $M_X = 8.5 \pm 1.5M_{sun}$ and an inclination of $65 \text{ deg} \pm 9 \text{ deg}$. The observed infrared color is consistent with that expected of a K dwarf secondary. If the accretion disk continuum is given by $f\lambda \sim \lambda^{-1.8}$, as observed in other quiescent X-ray novae, we constrain the accretion disk contribution to the K' flux (independently of optical estimates) to $\leq 12\%$.

4 Two Neutron Star SXT in Quiescence

A key part of our paper on evidence for event horizons in black holes was determining the x-ray luminosities of similar systems WITHOUT event horizons - the neutron star x-ray nova. Two of the five such systems included in our study were 4U 2129+47 and EXO 0748-676. We plan to submit this paper to ApJ by the end of 1996. The abstract is below.

Two Neutron Star SXT in Quiescence, 4U 2129+47 and EXO 0748-676

M. R. Garcia and P. C. Callanan, in prep for ApJ 1996

We report on x-ray observations of two soft x-ray transients (SXT) containing neutron stars, 4U 2129+47 and EXO 0748-676. Our emphasis is on the quiescent properties of these sources, but we make comparisons to their outburst properties as well.

The x-ray spectrum and lightcurve of the eclipsing Low-Mass X-ray Binary (LMXB) 4U 2129+47 is measured with the ROSAT PSPC during its current quiescent state. This is the first such measurement for an accretion disk corona x-ray binary in a low state: these observations may provide new insights into the structure of LMXBs in quiescence. The quiescent x-ray luminosity of $\sim 10^{32.9} \text{ erg/s}$ and blackbody temperature of $kT \sim 0.22 \text{ keV}$ are similar to other quiescent LMXB. The quiescent x-ray light curve appears to show orbital modulation, but the statistics are insufficient to distinguish between a v-shaped partial eclipse (as seen in the high state) or a total, square wave eclipse. The similarity in the luminosity and temperature to other (non-eclipsing) quiescent LMXB implies that the vertical structure in the disk which blocked our direct view of the neutron star in the high state has collapsed, and the neutron star is seen directly.

EXO 0748-676 was serendipitously observed with the Einstein IPC in quiescence before it was discovered as a bright transient with EXOSAT. Our re-analysis of this quiescent observation finds $L_x \sim 10^{34.1}$, and blackbody temperature of $kT \sim 0.21$ keV, again similar to other LMXBs in quiescence.